WORKSHOP REPORT ON ATOMIC BOMB DOSIMETRY—REVIEW OF DOSE RELATED FACTORS FOR THE EVALUATION OF EXPOSURES TO RESIDUAL RADIATION AT HIROSHIMA AND NAGASAKI

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Abstract—**Groups of Japanese and American scientists, supported by international collaborators, have worked for many years to ensure the accuracy of the radiation dosimetry used in studies of health effects in the Japanese atomic bomb survivors. Reliable dosimetric models and systems are especially critical to epidemiologic studies of this population because of their importance in the development of worldwide radiation protection standards. While dosimetry systems, such as Dosimetry System 1986 (DS86) and Dosimetry System 2002 (DS02), have improved, the research groups that developed them were unable to propose or confirm an additional contribution by residual radiation to the survivor's total body dose. In recognition of the need for an up-to-date review of residual radiation exposures in Hiroshima and Nagasaki, a half-day technical session was held for reports on newer studies at the 59th Annual HPS Meeting in 2014 in Baltimore, MD. A day-and-a-half workshop was also held to provide time for detailed discussion of the newer studies and to evaluate their potential use in clarifying the residual radiation exposure to atomic bomb survivors at Hiroshima and Nagasaki. The process also involved a re-examination of very early surveys of radioisotope emissions from ground surfaces at Hiroshima and Nagasaki and early reports of health effects. New insights were reported on the potential contribution to residual radiation from neutron-activated radionuclides in the airburst's dust stem and pedestal and in unlofted soil, as well as from fission products and weapon debris from the nuclear cloud. However, disparate views remain concerning the actual residual radiation doses received by the atomic bomb survivors at different distances from the hypocenter. The workshop discussion indicated that measurements made using thermal luminescence and optically stimulated luminescence, like earlier measurements, especially in very thin layers of the samples, could be expanded to detect possible radiation exposures to beta particles and to determine their significance plus the extent of the various residual radiation areas at Hiroshima and Nagasaki. Other suggestions for future residual radiation studies are included in this workshop report.**

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INTRODUCTION

THE 2002 reassessment of radiation doses to survivors at Hiroshima and Nagasaki, designated as DS02, determined the initial radiation exposure of atomic bomb survivors to gamma rays and neutrons (Young and Kerr 2005). The primary purpose of the 2002 reassessment was to address a discrepancy between calculated and measured values for neutron activation in Hiroshima (National Research Council 2001). This discrepancy was mainly due to problems with neutron activation measurements and led to a lack of confidence in the earlier DS86 (Roesch 1987). Changes made from DS86 to DS02 were minor, but they fixed several problems with calculations of the air-over-ground transport for the initial radiation from the Hiroshima and Nagasaki bombs. DS86 and DS02 only briefly considered the possibility of some minimal contribution to the total whole body doses by residual radiation exposure.

During the 57th Annual Meeting of the Health Physics Society in Sacramento, CA, in 2012, a technical session and workshop were held to discuss the issue of residual radiation exposures to the atomic bomb survivors of Hiroshima and Nagasaki (Kerr et al. 2013). Based on the suggestions from this previous workshop and in recognition of the need for further review of this topic, a half-day technical session was held during the 59th Annual Meeting of the Health Physics Society in Baltimore, MD, in 2014. The chairpersons for the technical session were Isaf Al-Nabulsi and Masaharu Hoshi. In addition, a day-and-a-half workshop chaired by George D. Kerr and Stephen D. Egbert was also held during the meeting. The technical session and workshop allowed for participants to evaluate the use of data from many different research programs in clarifying the potential residual radiation doses to survivors of the Hiroshima and Nagasaki bombing.

The major topics of interest in this review of dose related factors for the evaluation of exposure to residual radiation at Hiroshima and Nagasaki are discussed in the following subsections of this report:

- Early radiation surveys at Hiroshima and Nagasaki;
- Potential sources and locations of residual radiation exposure:
  1. Neutron activated radionuclides in unlofted soil;
  2. Neutron activated radionuclides from dust stem and pedestal;
  3. Fission products and weapon debris from the nuclear cloud; and
  4. External and internal doses from residual radiation exposure.
- Potential use of retrospective luminescence measurements:
  1. Sample selection for retrospective luminescence measurements;
  2. Sample measurements of beta-particle and gamma-ray doses; and
  3. Sample calculations for beta-particle and gamma-ray doses.
- Populations of interest at Hiroshima and Nagasaki;
  1. Hiroshima atomic bomb survivors close to the hypocenter and "early entrants;"
  2. Atomic bomb survivors in known fallout areas;
  3. Survivors caught in fallout rain;
  4. Survivors who experienced epilation and their locations;
  5. Estimation of contact beta-particle exposures to residual radionuclides in Hiroshima.
  6. Potential health effects from beta-particle exposures to atomic bomb survivors based on studies of other exposed populations; and
  7. Validation of organ doses.
- Summary and Conclusions:
  1. Workshop suggestions for possible additional research on ground activation and potential dose from residual radiation; and
  2. Suggestions for possible research on health effects related to potential residual radiation exposures.

A list of the titles and contributors to the presentations made during the technical session and subsequent workshop that provided information and data used in the above sections are listed in Appendices A and B of this paper.

EARLY RADIATION SURVEYS AT HIROSHIMA AND NAGASAKI

The first U.S. radiation surveys at Hiroshima and Nagasaki were made by a Manhattan Engineering District (MED) team under the leadership of General Thomas Farrell (DNA 1980). This MED team made rapid radiation surveys at Hiroshima on 8–9 September 1945 and Nagasaki on 13–14 September 1945. A much larger MED team under the leadership of General Thomas Farrell made more extensive radiation surveys at Nagasaki during 21 September to 4 October 1945 and at Hiroshima during 3–7 October 1945 (Tybout 1946). The U.S. Naval Medical Research Institute (NMRI) also made extensive radiation surveys at Nagasaki during 15–27 October 1945 and at Hiroshima during 1–2 November 1945 (Pace and Smith 1959). The MED and NMRI surveys were supplemented by measurements made by Japanese scientists at both earlier and later dates (Arakawa 1962; Takeshita 1975; Imanaka 2011).

The MED survey team used two Lauritsen-Wollan (L-W) electroscopes and two portable Geiger-Müller (G-M) counters. The G-M counters were developed by the University of Chicago and made by the Victoreen Instrument Company (Tybout 1946; McRaney and McGahan 1980). The survey instruments were calibrated using gamma rays from a radium source, and the calibrations were made in terms of Roentgens per hour (R h^{-1}). The G-M counting tube was mounted inside a brass probe with a wall thickness of 0.16 cm (1/16 inch). There was an attempt to make measurements with the L-W electroscopes, but the calibrations of the electroscopes did not remain consistent from day to day, and the measurements were discarded due to unknown drifting within each day. Results of measurements made by the MED survey team with the G-M tube counters held at a height of 5 cm (2 inches) above the ground at Hiroshima and Nagasaki are shown in Figs. 1 and 2, respectively (Tybout 1946; Wilson 1956). Natural background was subtracted when the measurements were recorded, and contours were drawn on the figures.

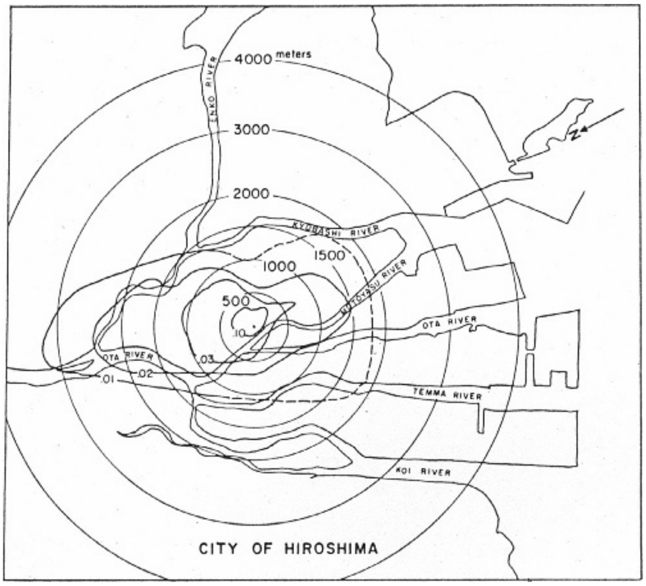

Fig. 1. Results of the radiation survey by the Manhattan Project Team at Hiroshima during 3–7 October 1945. The numerical values on the isodose contours in the figure are measured exposure rates in mR h^{-1} at 5 cm (2 inches) above ground (Tybout 1946; Wilson 1956). The values for exposure rates shown on the radiation contours about the hypocenter are 0.01, 0.02, 0.03, and 0.10 mR h^{-1}. The map is missing a measurement in a radiation hotspot on both sides of the Koi River, with a local peak of 0.045 mR h^{-1} found on the far western side of the Koi River.

The NMRI survey team used a G-M counter that was constructed "in house" for their measurements (Pace and Smith 1959; McRaney and McGahan 1980). The NMRI also calibrated their G-M counter in R h^{-1} using gamma rays from a radium source. During the surveys at Hiroshima and Nagasaki, the counter was placed at a fixed distance of 1 m above ground by means of a rigid support. A few measurements were also made with the counter placed at 5 cm (2 inches) above ground. The NMRI survey team observed that readings in the areas around ground zero in both cities did not change as the instrument height above ground was varied from 5 cm to 1 m; however, in the downwind contaminated areas, measurements taken at 5 cm above ground were approximately double those taken at 1 m above ground. They attributed the difference to an increased ratio of beta particle to gamma ray activity in the downwind areas (Pace and Smith 1959). The results of measurements made by the NMRI survey team with the G-M counters held at 1 m above ground at Hiroshima and Nagasaki are shown in Figs. 3 and 4, respectively (Pace and Smith 1959; McRaney and McGahan 1980).

While the survey results discussed in this section are important in defining areas for potential exposure to residual radiation in Hiroshima and Nagasaki, it must be remembered that the surveys discussed in this section were made between 1 and 3 months (mo) after the bombings. From the first of September through the end of October of 1945, there was considerable rainfall in both Nagasaki and Hiroshima as shown in Fig. 5 (Takeshita 1972), much of it during the Makurazaki typhoon on 17–18 September 1945 (Ishikawa and Swain 1981). In Hiroshima, the rivers flooded, most of the bridges were lost, and large areas of ground, including some near the hypocenter, were submerged (Ishikawa and Swain 1981). There was

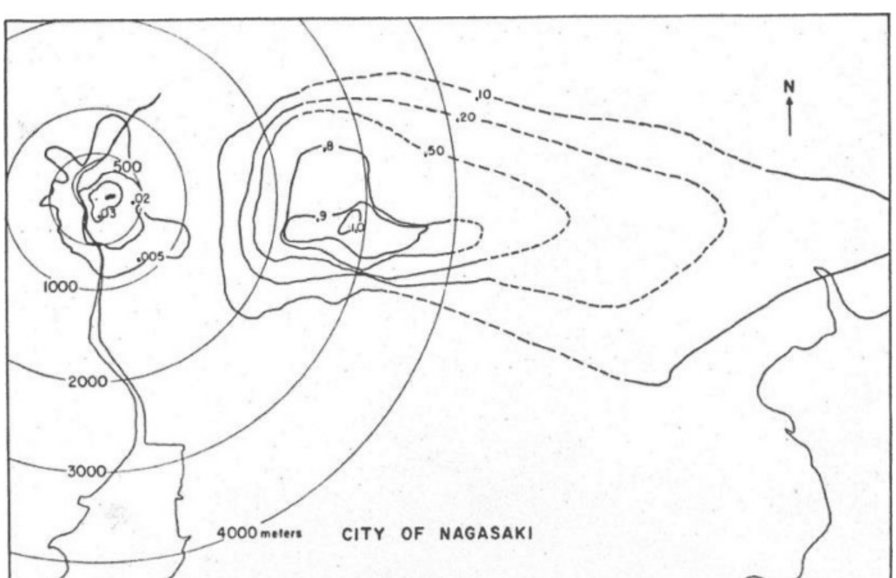

Fig. 2. Results of the radiation survey by the Manhattan Project Team at Nagasaki during 21 September to 4 October 1945. The numerical values on the isodose contours in the figure are measured exposure rates in mR h^{-1} at 5 cm (2 inches) above ground (Tybout 1946; Wilson 1956). The values for the exposure rates shown on the radiation contours about the hypocenter are 0.005, 0.02, and 0.03 mR h^{-1}, and the values shown on the radiation contours in the Nishiyama area to the east of Nagasaki are 0.1, 0.2, 0.5, 0.8, 0.9, and 1.0 mR h^{-1}.

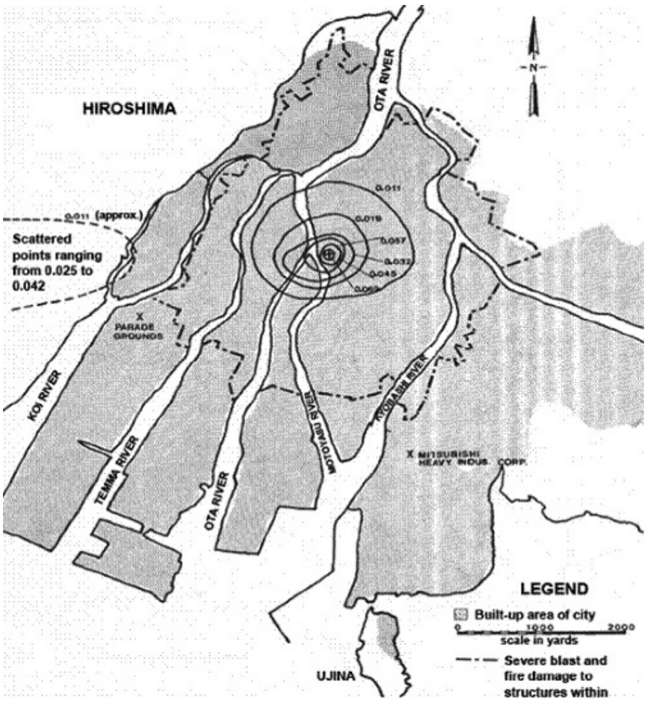

Fig. 3. Results of the radiation survey by the US Naval Medical Research Institute (NMRI) at Hiroshima during 1 and 2 November 1945. The numerical values on the isodose contours in the figure are exposure rates from gamma radiation in mR h^{-1} at 1 m above ground (Pace and Smith 1959; McRaney and McGahan 1980). The values shown on the radiation contours about the hypocenter are 0.011, 0.019, 0.032, 0.045, 0.057, 0.069 mR h^{-1}, and the value shown on the radiation contour in the Koi-Takasu area to the west of Hiroshima is approximately 0.011 mR h^{-1}.

undoubtedly leaching and weathering of radioactive products and possibly uneven removal and relocation of the radioactive products in both Hiroshima and Nagasaki during the months of September and October 1945.

The beta particle emission rates from soil samples left unperturbed in the Nishiyama area of Nagasaki decreased much faster than measurements from soil samples taken out of the field into a protected environment. This difference was attributed to the effects of leaching and erosion by frequent rains in the field (Shinohara et al. 1953; Ishikawa and Swain 1981). When the field measurements were plotted on semi-logarithmic graph paper against total rainfall in millimeters (mm), the decay curves for these samples were found to be nearly linear with coefficients ranging from 0.55×10^{-3} mm^{-1} to 1.02×10^{-3} mm^{-1} (Takeshita 1972) with an average over all sets of measurements of approximately 1.0×10^{-3} mm^{-1} (Takeshita 1975). At Hiroshima, no similar systematic and consecutive measurements of fallout were made (Takeshita 1975). If a similar situation were to have occurred in the "black rain" areas at Hiroshima, then the fission product exposure rate, I, at the time of the measurements would be equal to $I_0 \times (t/t_0)^{-1.2} \times e^{-kQ}$, where t is the time of the measurement, t_0 is the time of deposition of the fallout, I_0 is the initial intensity at time t_0, k is 1.0×10^{-3} mm^{-}, and Q is the total rainfall in mm between t_0 and t (Takeshita 1972). The total rainfall at Hiroshima and Nagasaki for several months after the bombings is shown in Fig. 5 (Takeshita 1972). It has been suggested by Egbert and Kerr (2012) that estimates of I_0 based on measurements of fallout on the ground made several weeks to several months after the bombing at Hiroshima may have extremely large uncertainties.

POTENTIAL SOURCES AND LOCATIONS OF RESIDUAL RADIATION EXPOSURE

Two distinct sources of human exposure to residual radiation were found in several surveys after the bombings at both Hiroshima and Nagasaki: (1) radioactivity from the neutron activation of the ground, including buildings, recognized by well-defined isodose contours that were roughly circular areas about the hypocenters of the explosions; and (2) radioactivity from weapon debris consisting of radioactive fallout of fission products, unburnt nuclear fuel (i.e., U or Pu), and neutron activated components from the

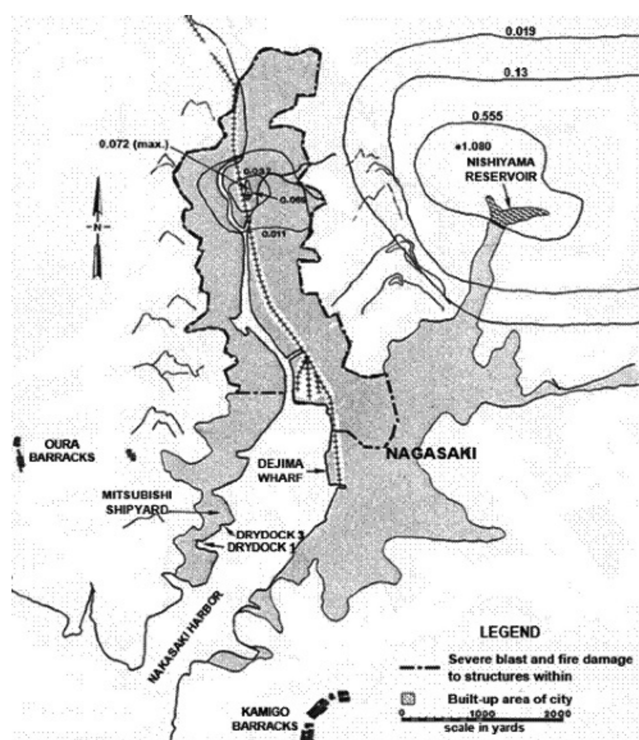

Fig. 4. Results of the radiation survey by the U.S. Naval Medical Research Institute (NMRI) at Nagasaki during 15 to 27 October 1945. The numerical values on the isodose contours in the figure are measured exposure rates from gamma radiation in mR h^{-1} at 1 m above ground (Pace and Smith 1959; McRaney and McGahan 1980). The values on the radiation contours about the hypocenter are 0.011, 0.032, 0.069, 0.072(max) mR h^{-1}, and the values on the radiation contours in the Nishiyama Reservoir area are 0.019, 0.13, 0.555, 1.080 mR h^{-1}.

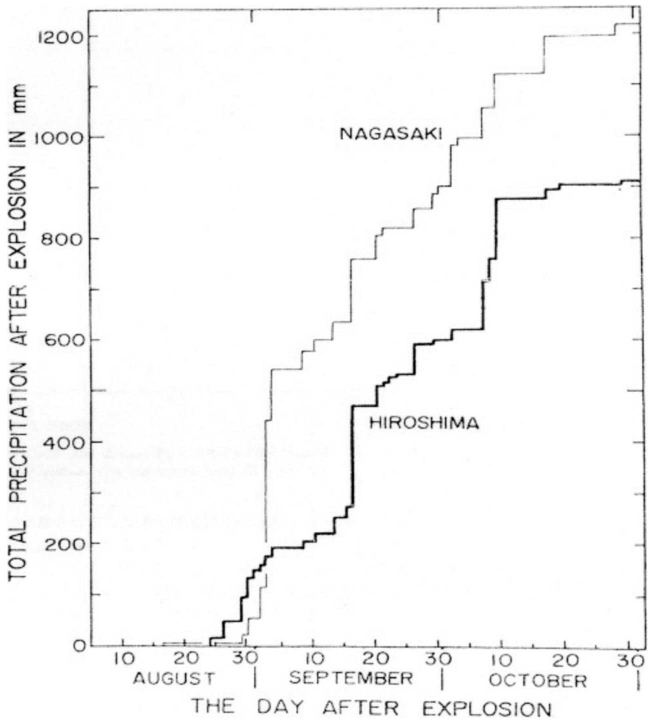

Fig. 5. Total rainfall as a function of each day after explosion during the 3 mo following the bombings at Hiroshima and Nagasaki on 6 and 9 August, 1945, respectively (Takeshita 1972). The precipitation totals shown in the figure are from records of the Hiroshima Meteorological Observatory and the Nagasaki Water-Supply Department (305 mm = 1 foot).

5 ton (4.54×10^3 kg) weapons found at distances of approximately 2,000 m (1.3 miles) in downwind directions from the hypocenters (or ground zero points) of the explosions, as shown in Figs. 3 and 4 (McRaney and McGahan 1980). In order to determine the residual radiation doses received by survivors, it is important to understand the magnitude of these sources and how the sources were distributed and redistributed over all surrounding areas.

Most reports state that rain started falling in the Koi-Takasu area of Hiroshima and the Nishiyama area of Nagasaki about 30 min after the explosions. The rains lasted most of that day, which is indicative of precipitation scavenging, also known as "wet deposition" or "rainout" (Okajima et al. 1987; Shizuma et al. 1996). A black-colored rain was reported by the residents of Koi-Takasu because the rain made black spots on white clothing (Henshaw and Brues 1947). It has been determined that the rain in the Koi-Takasu area contained weapon debris and dust lofted into the atmosphere plus soot and cinders from the firestorm in the hypocenter area at Hiroshima (Fields et al. 1989; Fujikawa et al. 2003; Shizuma et al. 2012a and b). No firestorm arose in Nagasaki, and the rain in the Nishiyama area was reported by residents to be a "yellow-brown rain" (Pace and Smith 1959). Because of this early arriving presence of radioactive fission products and other weapon materials from the nuclear explosions, rainout from the cloud cap to the H_2O saturated stem is suspected of being responsible for the weapon debris fallout in these outlying areas at Hiroshima and Nagasaki.

Neutron activated radionuclides in soil

The ground composition affects both the initial radiation transport in an air-over-ground environment and the neutron activation of the soil around the hypocenters of the explosions. In 1969, the Japanese National Institute of Radiological Science (JNIRS) reported a study involving fifty soil samples from Hiroshima and Nagasaki (Hashizume et al. 1969). Their study focused on a few isotopes of the various chemical elements in soil that were made radioactive very close to the surface by incident thermal neutrons from the air and higher-energy neutrons that were thermalized by the water content of the soil. The water content of the fifty soil samples collected in the summer of 1966 ranged from 25 to 35% of the soil's dry weight. A mean value of 30% was adopted by JNIRS for the water content of natural soil at the time of the bombings in Hiroshima and Nagasaki.

In 1983, a study at the Oak Ridge National Laboratory (ORNL) provided additional data on the chemical composition of dry soil samples from two undisturbed areas in each of the two cities (Kerr et al. 1983). The soil samples were sterilized by heating at the port of entry by the U.S. Department of Agriculture. After arriving at ORNL, the soil samples were dried by heating for an additional 24 h at 105–110 °C to further remove any unbound water and then pulverized to pass through a No. 100 mesh screen with 150-micron openings. Standard chemical techniques relying on gravimetric analysis were used to obtain data on a few chemical elements such as hydrogen, nitrogen, and oxygen. However, the primary techniques for obtaining data on trace elements in the soil samples were atomic emission spectrometry and neutron activation analysis. Measured values for 47 major and trace elements in the soil samples are provided in Table 7 on page 79 in Volume 1 of the DS86 report (Kerr et al. 1987), and the elemental compositions for natural soil in the hypocenter areas of Hiroshima and Nagasaki using data from both the JNIRS and ORNL studies are provided in Table 4 on page 144 in Volume 1 of the DS02 report (Santoro et al. 2005).

During the technical session and following workshop, several presentations were made that clearly identified the neutron-activated radionuclides in soil that were major contributors to the external dose from gamma rays and beta particles. These presentations were prepared by G. D. Spriggs, R. L. Weitz, M. Yu, Orlov et al., and V. Kryuchkov et al. (Appendices A and B). Based on these presentations, the major neutron-activated radionuclides contributing to the external dose of the atomic bomb survivors were: ^{24}Na, ^{28}Al, ^{31}Si, ^{32}P, ^{38}Cl, ^{42}K, ^{45}Ca, ^{46}Sc, ^{56}Mn, ^{59}Fe, ^{60}Co,

Table 1. Emission characteristics of the most significant neutron-induced radionuclides in soil of the hypocenter areas at Hiroshima and Nagasaki from presentation by Weitz (Appendix A).

Most significant neutron-induced radionuclides			
Radionuclides	Half-life	Average beta energy (MeV decay^{-1})	Average gamma energy (MeV decay^{-1})
^{24}Na	15.0 h	0.6	4.1
^{28}Al	2.24 m	1.2	1.8
^{31}Si	2.62 h	0.6	0
^{32}P	14.3 d	0.7	0
^{38}Cl	0.622 h	1.5	1.4
^{42}K	12.4 h	1.4	0.3
^{45}Ca	165 d	0.1	0
^{46}Sc	84 d	0.1	2.0
^{56}Mn	2.58 h	0.8	1.7
^{59}Fe	45 d	0.1	1.2
^{60}Co	5.25 y	0.1	2.5
^{134}Cs	2.3 y	0.2	1.5

and ^{134}Cs. A summary of the radiation emission characteristics of these various radionuclides is provided in Table 1 from the presentation by R. L. Weitz (Appendix A). These radionuclides are also important in the considerations of the internal dose from inhalation of dust-borne radionuclides by survivors at both cities.

The radionuclides from neutron-activated soil can be divided accordingly into two different sources: *fixed* and *lofted*. The *lofted* component consists of radionuclides drawn or scoured off the surface under the explosion primarily by the blast wave from the explosion and then by the inflow of winds created initially by the buoyant fireball that forms the cap of the mushroom cloud at both Hiroshima and Nagasaki (Figs. 6 and 7). The amount of soil that is lofted is highly dependent on the height of the burst and the type of surface and Japanese structures about the hypocenter of the explosion. At Hiroshima and Nagasaki, the amount of soil lofted above the dust pedestal was rather small due to the relatively high burst altitudes and moderate yields of the explosions as discussed in detail during the presentation by G. D. Spriggs (Appendix A). The mass, lofted high into the dust pedestal and stem due to the blast-demolished soil-containing roofs and walls, was potentially larger than that from the typical scouring of the ground surface by the blast wave.

The *fixed* component consists of the radionuclides that were not lofted into the stem or pedestal during the

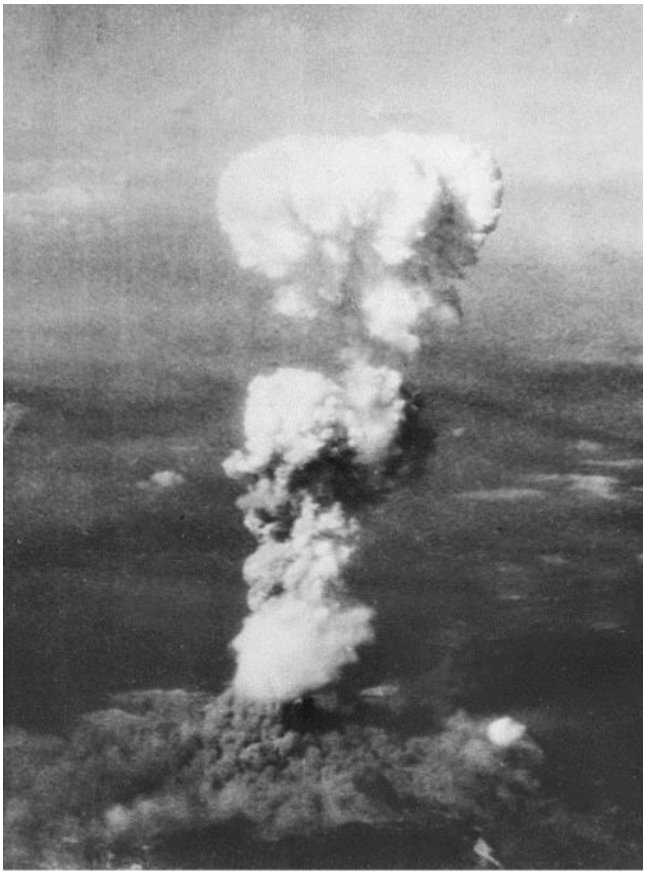

Fig. 6. Photograph of the cap of the mushroom cloud, gap between the cap and cumulus cloud at top of dust stem, dust stem, and dust pedestal (or dust base) of the Hiroshima explosion (National Archive).

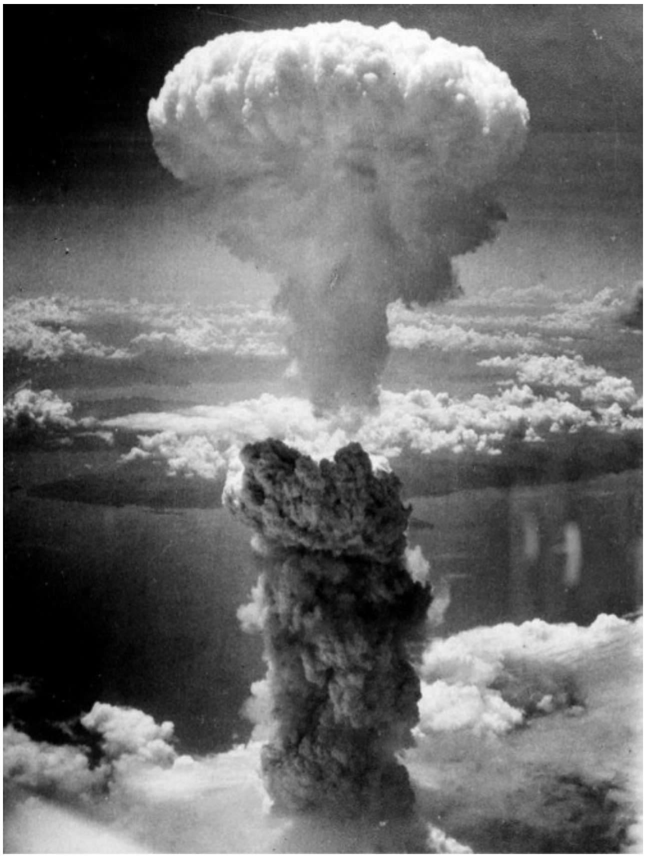

Fig. 7. Picture of the cap of mushroom cloud, gap between the cap and cumulus cloud at the top of dust stem, and the dust stem of the Nagasaki explosion (National Archive).

explosion. At Hiroshima, half of the radionuclides are activated within the first 7 cm below the ground surface (99% is within 25 cm) and most remain fixed at the position where they were created. At Nagasaki, this half depth is 5 cm and 7 cm for prompt and delayed neutron activation, respectively. Because approximately half of all soil activation at Nagasaki is the result of delayed neutron activation after the much stronger blast wave arrived and destroyed the cohesion of the soil and buildings, it is not clear where these radionuclides were eventually deposited following the explosion. The fixed soil also includes the un-demolished "mortar" that held the roof tiles in place and the "plaster" soil that held the straw and woven bamboo within the walls of houses and other wooden buildings. The subsequent decays of the radionuclides from these various sources produce the activation ring-shaped contours that were centered about the hypocenters of the explosions (Figs. 1 through 4).

Neutron activated radionuclides from dust stem and pedestal

The dust stem and pedestal of the atomic bomb explosions at Hiroshima and Nagasaki contained the lofted neutron-activated radionuclides from soil particles and other building materials found in the hypocenter areas of the two cities. Some of the most significant of these other urban materials are the ones used in the construction of typical Japanese houses prior to the time of the bombings. These various materials include ceramic roof tiles, soil mortar used to set the roof tiles, bricks, concrete, wood, and mud plaster on the interior walls of houses. Several neutron-activation studies have shown that the most significant radionuclides produced in these urban materials are essentially the same as those found in the neutron-activated soils at Hiroshima and Nagasaki (Arakawa 1962; Hashizume et al. 1969; Endo et al. 2013). Thus, the radioactive decay curves have been found to be approximately the same for soil and other materials lofted upward by the reflected shock wave and the following upward draft of the buoyant fireballs from the explosions.

Fission products and weapon debris from the nuclear cloud

The cap of the multi-segmented nuclear cloud contained radionuclides from fission products, unburned fuel from the critical mass in the weapon, neutron-activated weapon components, and neutron activated airborne pollutants, such as ash and coal impurities in smoke from homes or factories. Due to the height of burst and yield, an initial gap of about 250 m (Nagasaki) or 350 m (Hiroshima) occurred between the nuclear weapon debris in the cap of the mushroom cloud and its trailing condensed-moisture stem (Figs. 6 and 7). Thus, the cap did not co-mingle with any surface region debris in the trailing stem, especially during the condensation phase of the weapon debris as discussed in the presentation by G. D. Spriggs (Appendix A). Because no dust particles were drawn into the caps of the nuclear clouds from the two explosions, most of the 5 tons of weapon debris condensed into very small submicron-sized particles. At that size without subsiding airflow or scavenging into rainout, they would fall at a rate of less than 1 m per minute and not reach the earth's surface in times pertinent to the problem. The nuclear cloud of the Hiroshima explosion was tracked by aircraft to the west coast of the United States and as far inland as Lake Michigan (Blair et al. 1945; Strohl 2001).

In contrast, the mean particle size in the surface-connected trailing stem is correlated to that of the several particle-size distributions for the entrained soil and mud/wood building debris in the hypocenter areas at Hiroshima and Nagasaki. The basic grains within these soil particles can range in size from a few microns to several centimeters in diameter (Spriggs and Ray-Maitra 2007; Endo et al. 2013; Sakaguchi et al. 2013). The radial turbulent diffusion in this trailing stem removes the largest particles from the updraft, and these will fall to the ground from the heights to which they were lofted. Thus, the primary source of residual radiation in areas surrounding the hypocenters at Hiroshima and Nagasaki, where the proximal survivors were located, was due to the neutron activation of soil and other residual materials. The residual radiation source in the cap is very large compared to other residual radiation sources, but the very low settling rates of the submicron-size particles would have kept most of the fission products and weapon debris in the nuclear cloud lofted for periods of several years unless brought down to the earth's surface by rainout.

Some fission products, however, have been found randomly within several kilometers of the hypocenter at Hiroshima, most significantly downwind west toward the Koi and Takasu area. The fission product ground contamination was analyzed by Shizuma et al. (1996) from soil samples collected 3 d after the bombing. They found that only one of the analyzed 22 soil samples, collected on 9 August 1945, had a significant amount of the fission product ^{137}Cs; 10 of the samples collected at ground ranges of 1–4 km from all compass directions had barely detectable amounts of ^{137}Cs; the remaining 11 samples collected at ground ranges of 0.3–5.3 km samples had no detectable ^{137}Cs during the several day intervals used for the counting of gamma rays from the samples. Except for the one large measurement (4 R), each had cumulative exposure less than 0.2 R, significantly less than estimated from survey measurements, presumed originally by Japanese scientists to be from activated dust and debris but subsequently shown to contain traces of fission products. Thus, the data suggest

Table 2. Summary of projected dose estimates (μGy) to an adult male from inhalation of neutron activated soil near the Hiroshima atomic bomb dome and Nagasaki University from presentation by Eckerman (Appendix A).

Summary of projected inhalation dose estimates (μGy)				
	Colon	Active Marrow	ET-Region	Lung
Hiroshima Atomic-Dome Soil				
100 h	8.72 – 9.55	9.04 – 9.11	541 – 543	8.32 – 9.63
First year	8.80 – 9.63	9.10 – 9.30	542 – 544	8.43 – 10.3
Nagasaki University Soil				
100 h	1.98 – 2.47	1.79 – 1.84	113 – 114	1.68 – 2.44
First year	2.07 – 2.56	1.84 – 1.99	114 – 115	1.85 – 3.04

that fission products may have been deposited in trace amounts at locations in various directions between 1 km and 4 km from the hypocenter. More important is the fact that there is no indication of fission product deposition within 1 km of the hypocenter.

Rain with a potential for selective scavenging from the various total debris in the nuclear cloud of the Hiroshima explosion was reported over a large area in a northwest direction relative to the hypocenter at that city (Takeshita 1975; Imanaka 2011; Masuda 2011). However, the Koi-Takasu area to the west of Hiroshima was the only confirmed area of fission product fallout during the various radiation surveys conducted immediately after the bombing at Hiroshima (Fig. 3). The dose rates from ground contamination in the Koi-Takasu area of Hiroshima were quite small compared to those found in the Nishiyama area of Nagasaki (Fig. 4). For example, the largest dose rate due to gamma rays from ground contamination at Koi-Takasu was only 4% of the maximum found in the Nishiyama area at Nagasaki (Pace and Smith 1959; Takeshita 1975).

In order to generate the small amounts and spatially non-uniform ground patterns of fission products all around Hiroshima beyond 1 km and a single downwind hotspot, a two-stage rainout scenario was postulated[§§§§§§] from the two days of discussions. This virtual "fallout" process resulted from a unique coupling of the rainout from the cap of the nuclear cloud with the separately formed rainout in the turbulent trailing stem and subsequently higher firestorm cloud. There are several other event-specific conditions in both Japanese cities that encourage consideration of complex fallout scenarios that were absolutely excluded for similar yields and heights of burst at the Nevada Test Site, such as the high-humidity conditions, moisture released from the burned Japanese wooden structures and combustible interiors, interfering secondary shock waves due to structures and terrain, large area brackish rivers and other non-soil surfaces around the hypocenter, and other channels due to firebreaks, streets, and rivers leading radially away from the hypocenter area. The fission product deposition scenario starts in the first minutes and lasts for 1-2 h after the explosion. On the other hand, the ground and many structural materials are immediately activated, and then lofted portions are deposited from seconds (for the outer pedestal region) to minutes and hours depending on particle size and their lofted height on their way into the rainout from the broad firestorm cloud.

[§§§§§§]Scenario postulated by J.E. Cockayne during discussions at the 59th Annual Meeting of the Health Physics Society in Baltimore, MD, in July 2014.

External and internal doses from residual radiation exposure

Neutron activation of soil yields a number of beta-gamma emitters that may contribute additional radiation dose both external and internal to the body following dust-borne inhalation. The deposition of inhaled particulates within the respiratory tract is a function of airborne dust (particle size distribution, chemical form, etc.) and respiratory function (tidal volume, respiration frequency, nose vs. mouth breathing, etc.). Activity deposited in the respiratory tract is cleared by (a) mechanical processes (transported by the mucus lining of the airways) and swallowed, thus entering the gastrointestinal (GI) tract; (b) absorption to blood (systemic circulation) following disassociation from the dust particle; and (c) biological transfer by macrophages to the respiratory lymph nodes. Activity entering the GI tract may irradiate the segments of the tract and enter systemic circulation. Activity in the systemic circulation can be taken up by organs and tissues of the body and subsequently removed from the body through urinary or fecal excretion and radioactivity decay. Mathematical models describing the fate of radionuclides within the respiratory and gastrointestinal tracts and within the systemic circulation have been formulated by the International Commission on Radiological Protection (ICRP 1994). A bounding estimation of inhalation dose to an adult male has been performed by Eckerman (Appendix A), which indicated that doses to colon, lung, and marrow appear to be less than that from external exposure to the gamma rays from fixed soil activation in the same area (Table 2). The highest radiation doses would affect the extrathoracic regions of the respiratory tract and were estimated to reach 0.5 mGy from soil near the Hiroshima atomic bomb dome and 0.1 mGy from soil near Nagasaki University. Better estimates would require more accurate details regarding the exposure event and improved respiratory tract, biokinetic, and anatomical models (Leggett et al. 2013).

The external gamma-ray exposure to early entrants into the hypocenter areas in Hiroshima and Nagasaki within a few hours of the bombings has been evaluated previously by Imanaka and colleagues (Imanaka et al. 2008, 2012). Their previous evaluations indicate that the gamma-ray exposure rates in the hypocenter areas decrease rapidly with time due to the short half-lives of the dominant radionuclides in soil (Table 1). For example, the exposure rates were found to decrease by a factor of 1,000 at the end of 1 d and a factor of 1,000,000 at the end of 1 wk after the explosion, and the gamma exposure rates were found to decrease by a factor of 10 at a distance of 500 m from the hypocenter and a factor of several hundred at 1,000 m from the hypocenter. Thus, the evaluation of the radiation exposure to early entrants into the hypocenters requires detailed information on the time of entrance into the hypocenter area, distance from the hypocenter with time, and duration of their stay within the critical area (Imanaka et al. 2008, 2012). These earlier studies of Imanaka and his colleagues need to be updated using results of more recent studies of neutron-activated radionuclides in soil of the hypocenter areas at each of the two cities.

POTENTIAL USE OF RETROSPECTIVE LUMINESCENCE MEASUREMENTS

The DS02 studies (Young and Kerr 2005) resolved the neutron discrepancy issue in the initial radiation exposure (Straume et al. 1992) and eliminated the possibility of neutrons being a significant contributor to survivor organ doses (Cullings et al. 2006), even when variable functions for the relative biological effectiveness of neutrons that take on large values at very low doses are considered (Cullings et al. 2014). Thus, validating the DS02 dosimetry for gamma rays has become of primary importance in current studies (Egbert and Kerr 2012). Fortunately, hundreds of ceramic and brick samples were collected and documented since the 1960s from many structures in the two cities (Young and Kerr 2005). Several samples were collected, typically from each building, for use in previous thermal luminescent (TL) studies. The samples were chosen to be on the exposed surface of buildings or roofs and in line-of-sight to the bomb. This maximized the initial radiation measurements and reduced shielding uncertainty.

The first few millimeters of the ceramic surface were removed to ensure electronic equilibrium had been reached within the sample and the absorbed dose in the sample was equal to the kerma from gamma rays. For each sample, a background was determined for the ceramic's naturally occurring radioactive constituents plus the sample's exposure to terrestrial and cosmic radiation. The uncertainty in these background radiation measurements was reduced by using samples of a known and young age. The effects of the ceramic location, position, and shielding on all DS02 radiation components were calculated. These various selections and adjustments were very important in order to have a measurement to validate the calculated DS02 free-in-air (FIA) gamma-ray dose at 1 m above ground.

Agreement between the TL measurements and DS02 calculations was considered excellent over the large range of gamma-ray doses from above 100 Gy down to below 0.1 Gy as shown in Fig. 8 from the presentation by S. D. Egbert (Appendix A). However, each dose regime showed obvious discrepancies. Using the most rigorous TL comparisons from the DS02 report at the Nagasaki hypocenter, the TL measurements are lower than DS02 by −100 Gy (−35%), but they are only lower by −15 Gy (−15%) at a ground range of 400 m. At the Hiroshima hypocenter, the TL measurements are a good match to DS02, but they have become higher than DS02 by +40 Gy (+70%) at a ground range of 400 m. At ground ranges in both cities of 500 m and 1,200 m (1 to 50 Gy), the measurements corresponding to high survivor dose tend to be 10 to 20% less than the DS02 values. At doses less than 1 Gy, the few Nagasaki measurements were in good agreement with DS02, but the Hiroshima measurements corresponding to low survivor doses were approximately +0.1 to +0.2 Gy larger than the DS02 doses, with the amount varying according to the sample's direction from the hypocenter.

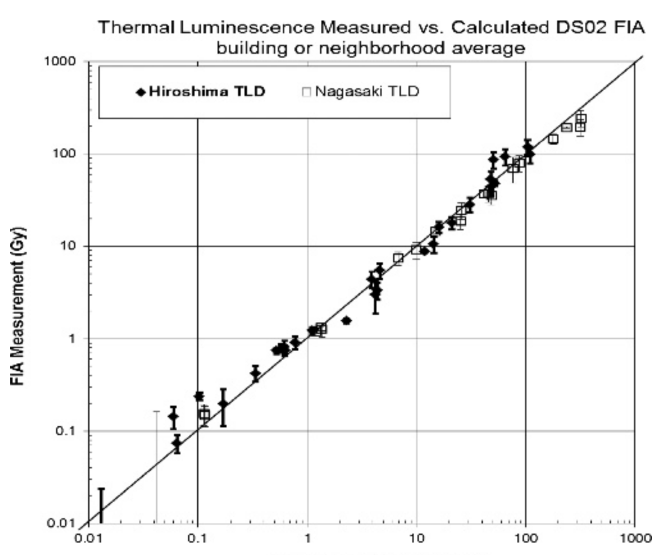

Fig. 8. Comparison of measured values from thermal luminescence (TL) measurements with DS02 calculated values of free-in-air (FIA) absorbed dose from gamma-rays at 1 m above ground at Hiroshima and Nagasaki [from presentation by Egbert (Appendix A)]. At ground ranges of 0, 500, 1000, 1500, 2000, 2500 m, the doses for Hiroshima are 120, 35.7, 4.22, 0.527, 0.0764, 0.0125 Gy, and for Nagasaki they are 328, 83.0, 8.62, 0.983, 0.138, 0.0228 Gy.

Evidence of exposure to residual radiation can be found in depth-dose profiles from measurements made using small crystal inclusions in thin slices of an exposed ceramic sample (Bailiff 1999; Bailiff et al. 2004). An example of a measured depth-dose profile from beta particles and gamma rays in a Hiroshima exposed ceramic-tile sample (H-4) from the sample collection at the University of Hiroshima is shown in Fig. 9. This figure is taken from the technical session presentation by Stepanenko (Appendix A). His single-grain optically stimulated luminescence (OSL) net quartz measurement is nearly constant with a value of approximately 1.08 Gy from the near surface of the tile sample to a depth of 22 mm within the sample, and it is 7% larger than the previous measurement in the DS02 Report (Young and Kerr 2005). The different energy deposition in a sample from beta particles and gamma rays was explained as follows: For a pure beta-particle exposure, the energy deposition (or absorbed dose) drops rapidly from the surface of the sample until it reaches a nearly constant bremsstrahlung level at a depth of approximately 5 mm (Fig. 9), and for a pure gamma-ray exposure, the energy deposition (or absorbed dose) rises from a very low value at the surface of the sample and reaches a nearly equilibrium value at a depth of approximately 5 mm in the sample.

Stepanenko's OSL measurement at the Medical Radiological Research Center in Obninsk suggests a beta-particle dose in the first few millimeters near the sample's surface (after the 0.1-mm black and very high density glazed layer was removed from the surface) that is consistent with a beta-particle dose of several tenths of a Gy above the neutron-activated soil at the Hiroshima hypocenter (Appendix A). This value was estimated using Weitz's calculated value of approximately 0.3 Gy for the beta dose at the Hiroshima hypocenter (Appendix A). To estimate the beta dose in this Hiroshima tile sample, absorbed dose calculations using the DS02 angular spectra for gamma rays incident on the sample need to be subtracted from the measurement, which was noted in Stepanenko's presentation and plans for further investigations. Besides measuring the beta-particle dose on the sample, the beta-particle energy from the radioisotopes unique to soil, such as ^{28}Al (2.9 MeV max.), ^{56}Mn (2.9 MeV max.), ^{24}Na (1.4 MeV max.) and ^{46}Sc (0.4 MeV max.) may be inferred by unfolding the depth dose profile compared to ^{38}Cl (4.9 MeV max.) that is unique to neutron-activated saltwater from the rivers at Hiroshima. It needs to be noted here that sample H-4 is not one of the excess TL dose samples reported in Egbert and Kerr (2012). The tiles with an excess of more than 0.2 Gy were found on buildings at greater distances, such as the Hiroshima University Faculty of Science, Radioisotope Building, and Red Cross Hospital. The OSL/TL measurements of some of these samples are now in progress at Stepanenko's laboratory as noted in his presentation at the workshop (Appendix A).

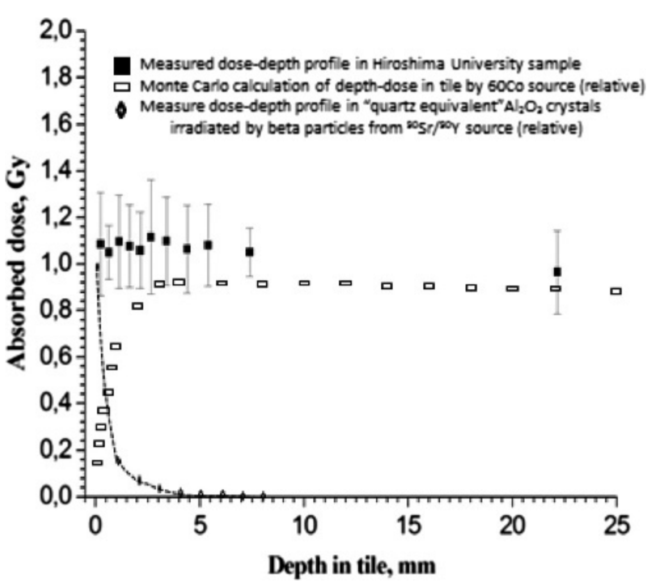

Fig. 9. Comparison of the depth-dose profiles from beta-particles and gamma-rays irradiations in a tile sample on an old Hiroshima University building from presentation by Stepanenko (Appendix A). The single grain optically stimulated luminescence (OSL) method was used and the high-density glazed layer from the surface of the tile was removed prior to the measurements.

The presentation by Woda (Appendix B) reported on the results of a study by the German Research Center for Environmental Health in collaboration with other organizations, using luminescence dosimetry in a radioactively contaminated area in the Southern Ural Mountains of Russia. He showed examples of measurements as functions of sample height above ground and depth within a sample. With OSL on quartz, anthropogenic doses can be measured down to values as small as 0.025 Gy. The minimum detection limit is mainly determined by uncertainty in the background radiation dose. Height profiles of radiation doses in bricks helped narrow down the contamination geometry of the gamma-ray source, and depth profiles of the radiation dose in the bricks helped to narrow down the energy of the gamma-ray source. This approach was successfully applied in validating the Techa River Dosimetry System (Balonov et al. 2006; Simon et al. 2007). Some background information on the advantages of both TL and OSL dosimetry can be found in a previous paper by Woda et al. (2009).

Woda encouraged the investigation of beta-particle profiles in additional tile samples to complement the work of Hoshi and Stepanenko. Although quite promising, this approach faces some serious challenges (buildup and sunlight bleaching effects). It was noted by Stepanenko during a discussion session that the 0.1-mm black and very hard glazed surface layer of the tiles blocked any sunlight bleaching effects and was removed during measurement preparation. As a complementary approach, Woda and his colleagues suggest looking into the depth-dose profiles for gamma rays in suitable brick samples from Hiroshima and Nagasaki. The photon spectrum is different for each soil activation radioisotope, and the initial gamma radiation is predominantly in the high-energy region. For example, the DS02 kerma-weighted average energy of the gamma rays is 2.4 MeV at a ground range of 0.5 km and rises linearly with distance so that it is above 4.0 MeV by 2.2 km at both cities (Egbert et al. 2007). Height profiles could also help to distinguish between cloudshine (i.e., air-transported radiation from the explosions of the bomb) and groundshine (i.e., radiation from neutron-activated soil). All of this depends on the availability of suitable samples for the areas of interest in the two cities.

Sample selection for retrospective luminescence measurements

Though not discussed in detail at the workshop, it will be important to select ceramic samples for retrospective dosimetry that are sensitive to residual radiation, available for measurement, and with known locations so as to be able to account for initial radiation. It is suggested to first use existing DS86/DS02 ceramic collections, samples located where a significant excess (or deficit) from the DS02 dose was observed (Egbert and Kerr 2012). These have been found in Hiroshima locations, which had (1) high likelihood of channeled soil deposition; i.e., SSW along the streetcar path to the city hall 0–1.5 km and NNE beyond the castle to 1.5–3 km, and in the far west Koi-Takasu area, 2–4 km from the Hiroshima hypocenter. There are locations (2) by the Hiroshima rivers, suggestive of a large excess gamma exposure of unknown origin; i.e., north in Teramachi 1 km, and south among the Hiroshima Bunri/Postal Savings/Red Cross buildings. In Nagasaki's Urakami valley, the only high excess TL dose was (3) near the Sakamoto cemetery in the direction of Nishiyama fallout.

Second, it is suggested that ceramic samples at locations unaffected by residual dose should be acquired in order to confirm and understand the differences. This is most likely accomplished by selecting samples that showed a deficit in TL dose compared to DS02; i.e., half of the Hiroshima samples that have TL measurements less than DS02 in NE, NW, SW, and SE directions, and at Nagasaki most samples have TL dose measurements less than DS02 (Egbert and Kerr 2012).

Finally, identify samples from the existing collections or acquire new ceramic samples that are likely to have high residual but low initial dose. These samples should be shielded from line-of-sight exposure to the bomb and be located in areas that are hypothesized to have had high residual doses based on previous TL measurements. They would be found behind large buildings, on a roof portion shielded by a thick parapet, or inside a concrete building. Any of these sample locations would reduce the initial radiation exposure by up to an order of magnitude and still receive potentially large residual radiation doses. Samples that are close to a contaminated surface or are highly contaminated themselves may be quite sensitive to beta radiation in the first mm. However, they would also be affected by local variations in the nearby contamination. Because beta radiation does not go beyond several meters in air, deeper samples that are shielded from initial radiation may be sensitive to the residual gamma radiation.

Sample measurements of beta-particle and gamma-ray doses

The preliminary work by Stepanenko shows promise that the residual radiation beta dose contributes enough to the OSL or TL signal to be observed in the first 5 mm beneath the ceramic surface. The method and technique developed by Stepanenko could be used on other samples according to the priority listed above. A ceramic should be analyzed in ≤0.5-mm slices in the first couple of mm, ≤1-mm slices over the next several mm, and a deep measurement at 10 or 20 mm to measure the gamma-only dose. The use of other OSL techniques where single grain determinations are performed in situ may also be appropriate (Bailiff 2006). Stepanenko expressed concern about the possible bleaching effects of the UV component of solar radiation. A lack of coating on the ceramic to prevent penetration of light could confound measurements with quartz grains close to the surface and thus needs to be studied and understood. However, a black glaze (0.1 mm in thickness) covered the surface of the samples that he tested and was removed prior to the measurements.

Woda suggested that it may be possible to use OSL sample measurements at depths to determine gamma spectra incident on ceramics. As gamma radiation is ~100 times more penetrating than beta radiation, the sample would need to be thicker to permit a wide range of depths and shielding. For this approach, the tiles are too thin, and thicker bricks would be required, perhaps with a thickness of as much as 100 mm (Bailiff et al. 2004).

Sample calculations for beta-particle and gamma-ray doses

Dose calculations in the samples will be required. First, as was done for DS02, the background radiation from internal and cosmic sources is obtained and subtracted from the measurement. DS02 has completed this for the existing sample collection. Second, calculate electron, photon, and neutron transport from all DS02 fluences incident on the ceramic sample. Third, calculate electron and photon transport from fallout incident on ceramic surfaces. This can be done for typical Hiroshima or Nagasaki hypocenter soil activation and likely scenarios with several soil thicknesses. Because the scenarios could vary, it may be necessary to explore these for each residual radioisotope. If any unaccounted OSL or TL vs. depth signal is found, further calculations may be needed to determine its origin.

POPULATIONS OF INTEREST AT HIROSHIMA AND NAGASAKI

A brief summary is provided in this section of the results from recent studies and work that has been ongoing for years on the impact of the residual radiation from the bombs on the survivors in Hiroshima and Nagasaki. This section also summarizes the presentations and discussions during the technical session and subsequent workshop (Appendix A and B). Hoshi et al. (1996) have pointed out that various exposed populations, both in Japan and in places such as Semipalatinsk, have experienced radiation effects, such as epilation, that are difficult to explain from calculated gamma exposures. Therefore, the discussions centered on possible effects from exposure to internal radionuclides and beta radiation that were not discussed in detail in the DS02 studies.

Hiroshima atomic bomb survivors close to the hypocenter and "early entrants"

During the technical session, Ohtaki and colleagues attempted to clarify the spatial-time distribution of the excess risk of solid cancer mortality among atomic bomb survivors in Hiroshima (Appendix A). The cohort (30,378 individuals with 4,292 solid cancer deaths) studied was from the Hiroshima University Atomic Bomb Survivor (ABS) database and exposed at 3.5 km or less from the hypocenter (Hoshi et al. 1996). The initial radiation doses were estimated through ABS93D, a dosimetry system that was developed at Hiroshima University using a similar algorithm to the DS86 dosimetry system used previously by RERF (Roesch 1987). They described their mathematical multistage carcinogenesis model for a single point exposure developed to explain the latent time from exposure to clinical diagnosis or mortality from cancer. The excess relative risk for solid cancer mortality from 1970 to 2010 was determined and indicated a significant effect for dependence on age at the time of the bombing for males only, also showing poor dependency on the initial radiation exposure from ABS93D's function of distance. The investigators speculate that adult males, who in order to assist the injured stayed within or entered a circular region with a radius of 2.0 km about the hypocenter during the period of 2 wk after the bombing, received significant residual radiation exposure. One question on this observation is whether the observed difference is influenced by underlying health effects, such as under-representation of healthy males who were away from the cities on military duty: What role did their individual behavior play in dosimetry just after the bombing?

During the workshop discussion period, Ohtaki and colleagues described an alternative dosimetry model using a power function of exposure with ground distance being better than initial radiation dose to provide support for the possibility of the contribution of residual radiation to cancer mortality in Hiroshima atomic bomb survivors (Appendix B). Their analysis also indicated a significant difference between radiation risk estimates for solid cancer mortality compared to the analysis by RERF using the Life Span Study (LSS) cohort and the DS02 dosimetry system. Ohtaki and colleagues estimated that the gender-averaged ERR for a 70-y-old Hiroshima survivor who was exposed to an initial dose of 1 Sv at the age of 30 y (ABS93D) was 0.24, which was about half of the value of 0.42 that was reported by RERF (DS02) for the combined Hiroshima/Nagasaki LSS cohort (Ozasa et al. 2012). It is important to note the comparison is between the ABS93D Hiroshima survivors and the RERF combined Hiroshima/Nagasaki cohort. However, the risk model used by Ohtaki and colleagues has a particular parametric form in regard to variables such as age at exposure and attained age, which is determined by the mechanistic theory involved and is different from the simpler descriptive models used by RERF.

Otani and colleagues presented evidence for increased cancer mortality in certified "early entrants" in Hiroshima and explored what kind of neutron-induced radionuclides in soil could be responsible (Appendix B). They used a multistage carcinogenesis model with the dose dependent on the half-life of neutron-induced radionuclides. Individuals who entered the city on the day of the bombing, 6 August, had a higher mortality risk compared to those who entered the city after 7 August. There was a significant interaction between "entrance-day" and "age at-time-of-bombing" on solid cancer mortality in both middle-aged men and women, which might indicate that middle-aged persons were moving around the city or staying in the city for relatively longer periods to search for family members and were therefore exposed to larger doses of radiation than younger or elderly persons. Considering the situation that almost the entire area within the 2-km radius of the hypocenter was burning by about 15:00 on the day of the bombing, ^{56}Mn (half-life of 2.58 h) was demonstrated to be the dominant activated material responsible for the elevation of mortality of 6 August entrants. The possibilities that other radionuclides—^{28}Al (2.24 min), ^{24}Na (15.0 h), ^{46}Sc (83.8 d)—were relevant for early-entrant exposures were statistically rejected. Questions were asked about the conclusion that ^{56}Mn is the most important radionuclide, and suggestions were made to consider not only half-lives but the amount of each radionuclide produced and the number and energies of gamma rays emitted by each radionuclide (the gamma-ray dose-rate constant) and time-dependent survivor behavior.

Atomic bomb survivors in known fallout areas

Cullings from RERF calculated the putative dose terms for external exposure to gamma rays from fallout in the known fallout areas of Koi-Takasu in Hiroshima and Nishiyama in Nagasaki (Appendix B). The putative doses were calculated for individual survivors based on their reported locations at the time of bombing by integrating exposure rates measured in early surveys in 1945, with correction for radioactive decay of a fission product radioisotope mixture in the fallout. The calculated dose terms were added to risk models. The resulting collective doses were small; about 90 person-Gy in Hiroshima and 180 in Nagasaki. In comparison to collective doses needed to cause a significant effect on cancer mortality in the LSS cohort, the results of this analysis so far do not support excess risk associated with the estimated fallout doses if assumed to be entirely from fission products. A suggestion was made to repeat this exercise assuming the fallout to be entirely activated soil relocated from the hypocenter and also to correct the measurement data for possible weathering due to the rains that occurred prior to the survey time. Assuming fission product decay rather than activation product decay could have resulted in greatly underestimating the doses.

Survivors caught in fallout rain

Grant and Sakata from RERF looked at the effects of fallout rain on mortality and cancer incidence among the LSS cohort of atomic bomb survivors (Appendix A and Sakata et al. 2014). The cohort studied consisted of 58,492 Hiroshima survivors and 28,117 Nagasaki survivors with information on whether they were "caught in fallout rain" from the Migration Questionnaire of 1955-56 and the Master Sample Questionnaire of 1956-61 and the latest RERF updates on mortality and cancer incidence. Data were analyzed by Poisson regression (Sakata et al. 2014). There were no increased mortality or cancer risks in the 20% of Hiroshima survivors who reported that they were exposed to rain (i.e., testing the hypothesis that the rain may have been associated with some of the risks of late health effects if it contained Hiroshima fallout). In the 2.6% of the Nagasaki survivors that responded yes, the association between causes of mortality risk and rain exposure was marginal, but there was no association with cancer risks. The authors reported the limitations of questionnaire studies, including wording and lack of detail, such as regarding subjects' clothing and head coverings. There were limitations also due to substantial numbers of Hiroshima survivors with missing rain information, including high rates of missing data and no data for time of rainfall, duration of the rain, and intensity of the rain. The analysis by Cullings of putative dose terms for external exposure to gamma rays in the compass quadrant associated with "black rain" in Hiroshima also does not support excess risk. Therefore, deleterious health effects from rain exposure are not evident in the LSS cohort. At the very least, rain exposure does not appear to have induced health effects of the same order of magnitude as that observed for the proximal atomic bomb survivors in the LSS.

Survivors who experienced epilation and their locations

Cullings from RERF reported on studies aimed at determining whether there are spatial patterns that would support hypotheses about causation of epilation (of scalp hair) by residual radiation sources (Appendix B). He discussed methods for selection of distal survivors with epilation (817 Hiroshima cases; 239 Nagasaki cases) from the Atomic Bomb Casualty Commission (ABCC) questionnaire data that were re-analyzed according to the method of Gilbert and Ohara (1984) using DS02 doses. This method checks for circular asymmetry about the hypocenters by comparing compass octants in various directions. The general conclusion was that statistical indications suggest distal cases of epilation are due to random errors in distance in the ABCC dataset.

The information on epilation in the Joint Commission Report was then reviewed (Oughterson and Warren 1956). The value of these data is that they are earlier than the ABCC data and include clinical examinations rather than self-reported effects. However, there are major problems with survivor locations, and RERF will continue to review the Joint Commission data. A major limitation of the Joint Commission data is that they do not represent a random sample of the population, as explained on page 463 of Oughterson and Warren (1956). The early authors did conclude that there was no definite indication for directional asymmetry for mechanical injuries, burns, and epilation. Cullings also reviewed the report of Kajitani and Hatano (1953), who examined 4,406 Hiroshima survivors between 15 October and 16 November 1945. Their report suggests a lower incidence of radiation injuries in the eastern part of the city due to many strong concrete buildings. Both from the ABCC/RERF data and other reports, there is no consistent and convincing evidence of a particular directional asymmetry in rates of epilation among distal survivors. It was observed that Culling's 50th-percentile dose estimate for epilation is 2 Gy with an assumed neutron dose weight of 1, significantly less than a 3-Gy threshold described below or the 2-Gy threshold mentioned by Tanaka et al. (2008).

Estimation of contact beta-particle exposures to residual radionuclides in Hiroshima

The research group of Stepanenko from the Medical Radiological Research Center, Ministry of Health of the Russian Federation, Obninsk, Russia, together with investigators at Hiroshima University (Appendix A), calculated the potential depth-dose distributions in biological tissue from beta-exposure by different neutron-activated radionuclides, taking into account the composition of soil near Hiroshima Castle. Calculations involved estimation of atoms of each target element per g of dry soil, neutron spectra at 1 m above soil surface, corresponding neutron activation cross sections, and the use of the Japanese human phantom. Monte Carlo simulation of electron transport in biological tissue was performed using MCNP-4C code with the EL03 Library of cross sections for electrons, and beta spectra of different neutron-activated radionuclides were accounted for. Using the standing Japanese human phantom, the cumulative beta dose to the skin of the head approached approximately 0.1 Gy, compared with 0.2 Gy in Tanaka et al. (2008) for skin on a vertical surface of the torso at the Hiroshima hypocenter.

Potential health effects from beta-particle exposures to atomic bomb survivors based on studies of other exposed populations

Shinkarev and colleagues provided scenarios to assess the exposure rate from beta particles, gamma rays, and the beta-to-gamma ratios from neutron-activated radionuclides in dust that fell in the area of wet fallout downwind from the hypocenter after the atomic bomb detonation in Hiroshima (Appendix B). The results show that a leading role in neutron activation of dust in the stem is due to thermalized delayed neutrons. They concluded that the methodological guides on external and internal dose assessment developed for the public living around the Semipalatinsk Nuclear Test Site can be applied with modifications to the conditions of residual radiation exposure to the Japanese atomic bomb survivors.

To address radiation-induced cataracts and epilation that were observed in the north and west regions of Hiroshima, Kryuchkov and colleagues assessed a combination of conditions that would provide dose from beta particles that was much higher than that from gamma rays and neutrons (Appendix B). Analysis of different conditions of irradiation showed that the predominance of external exposure from beta particles is possible when a thin-plane soil source of beta and gamma radiation is formed as a result of explosion and subsequent deposition processes. Once the thin layer thickness reaches a few mm, the beta dose is maximized and is unaffected by further changes in thickness. On the other hand, gamma dose is assumed to be proportional to the thickness of the deposition layer. They concluded that the maximal amount of neutron-activated dust and ash shifted from the hypocenter itself could not generate significant doses to organs and tissues located in the near-surface layer of the body. However, large doses could be obtained from wet deposition of fission products from the atomic cloud.

With regard to the possibility of developing oropharyngeal syndrome as a result of contact beta-irradiation of the oral mucosa due to the neutron-activated dust, Granovskaya and colleagues noted that death due to the oropharyngeal syndrome occurred at doses higher than 15 Gy, and ^{28}Al, ^{56}Mn, ^{42}K, and ^{24}Na are the main activation products (Appendix B). They also reported that, even in cases of heavy concentration of dust in the air, the dose due to contact beta-irradiation of the oral mucosa during 2 d could not exceed several mGy. Moreover, the symptoms of the oropharyngeal syndrome could develop (the threshold dose is 5 Gy) only if more than 10 g of hypocenter dust remained in the human oral cavity for a rather long period (a few hours). Thus, the symptoms similar to the manifestations of the oropharyngeal syndrome could not be solely caused by contact beta-irradiation of the oral mucosa due to the neutron-activated dust. With regard to epilation, neutron activated dust could not be the cause of the epilation among survivors who were at a distance of about 2.5 km downwind from the hypocenter at the time of the bombing. Epilation was observed among Chernobyl liquidators who received beta doses to the skin from residual radiation that were much higher than in Hiroshima (higher than 3 Gy). It was concluded that the gamma and beta doses were relatively low, and such doses could not be the sole cause of the reported epilation and oropharyngeal syndrome in the Japanese atomic bomb survivors. They recommended the need to compare the occurrence of these health effects among two groups: the survivors near the hypocenter at the time of explosion affected by various damaging factors (such as electromagnetic radiation, ultraviolet radiation, infrared radiation, and distress), and the early entrants group affected by residual radiation and distress. They also recommended the need to conduct additional studies to assess external doses from fission products due to wet deposition.

One participant at the workshop expressed the opinion that, based on the very unlikely ability to quantify any cofactor or synergistic role for such effects in combination with the effects of penetrating ionizing radiation, there did not appear to be a likely line of investigation at present. This participant further suggested that the most constructive near-term efforts would be to clearly establish the role of non-penetrating exposures to beta-particle radiations on the incidences of skin burn and epilation at Hiroshima and Nagasaki.

Validation of organ doses

Egbert calculated DS02 gamma doses for Hiroshima survivors at 41 different locations and compared these during a technical session presentation (Appendix A) with biodosimetric (tooth and chromosome) measurements, which had been converted previously to equivalent free-in-air gamma dose (Young and Kerr 2005). Two survivors were removed from the comparison: a 15-y-old's wisdom tooth that was not exposed since it would have erupted after 1945 and another survivor that was shown to have been at a closer distance based on the ^{41}Ca activation of that tooth (Rühm et al. 2010). Of the remaining 39, there was good agreement above 2 Gy. However, between 1 and 2 Gy, the measurements were larger than the calculation in several distinct directions away from the hypocenter, and below 1 Gy they were always larger, especially in these same distinct directions. The bio-dosimetric measurements deviated from DS02 in a geographical pattern, much like the TL doses (Egbert and Kerr 2012). It is acknowledged that there are many confounding factors that might be the cause of an apparent dose, so that this bio-measurement effort might not be accurate at low dose. However, it had been necessary to validate DS02 with high-dose TL and activation measurements. For that same reason, survivor doses to critical organs, though lower, should be validated as much as possible (Hirai et al. 2011). If it is not possible to resolve the dose anomalies by finding unrecognized sources of dose, then perhaps a larger dose uncertainty should be assigned to groups of survivors not in the vicinity of TL samples or without bio-dosimetry data that are consistent with DS02 (Grant et al. 2015).

SUMMARY AND CONCLUSION

During two days of technical presentations and workshop discussions, diverse views on the possibility of residual radiation exposures to the atomic bomb survivors at Hiroshima and Nagasaki were proposed. Discussions primarily focused on the potential residual radiation dose to the Hiroshima proximal survivors located at distances ranging from approximately 800 m to 2,200 m from the hypocenter.

One view, expanding on an RERF analysis (RERF 2012), is that there may be a small amount of residual radiation, but it does not have a statistically significant role in the dosimetry for the Hiroshima and Nagasaki survivors. Among the reasons behind this position are: a) the hypocenter of the detonation, where there was a large ground activation dose, could not be approached by survivors because of the destruction and post-detonation fires; b) higher than expected radiation health effects were not observed in black rain areas; and c) relief troops who later entered the hypocenter had biological effects and computed doses that suggested very small residual doses (average: 0.013 Gy, maximum: 0.1 Gy).

A second view, based on an analysis using a multi-step cancer model, suggests that residual radiation doses in Hiroshima would need to approach 1–2 Gy to match the modeled cancer incidence. This analysis suggests a residual gamma dose that could dominate over the initial radiation dose for most survivors. As such, a clear physical basis for such large residual doses is required.

Other investigators presented evidence that residual physical and biological dose measurements showed consistent patterns and magnitudes of dose that deviate from the DS02 initial dose, ranging from approximately a 20% decrease to about a 1-Gy increase. Suggested reasons for these discrepancies are substantial amounts of activated, lofted and dispersed soil that shielded survivors from a portion of the initial delayed radiation and subsequently exposed Hiroshima survivors to residual beta and gamma emissions. Such dose deviations could be comparable to the low DS02 initial dose for Hiroshima survivors beyond 1,500 m.

Despite these disparate views of the magnitude of residual radiation exposures, the problem is not intractable. Continued reconciliation of databases, dosimetry systems, and models are important for resolving residual dose issues. Useful new data can also be obtained using several newly proposed research ideas and measurements, such as beta and gamma depth-dose in TL ceramic samples and confirming city-wide distributions of the deposited layer of activated dust. New analysis and observations can be beneficial in differentiating between penetrating gamma doses and superficial and ingested exposure due to beta particles from ground material activation.

Workshop suggestions for possible additional research on ground activation and potential dose from residual radiation

- TL/OSL single-grain beta dosimetry (determine extent of residual dispersion, determine radioisotope from beta energy);
- TL/OSL single-grain gamma dosimetry for unfolding spectra (determine radioisotope from gamma energy);
- Collect and measure additional TL samples at locations that were shielded from initial radiation (determine extent and magnitude of residual dosimetry by removing initial dose);
- Comprehensive collection, archiving and assessment of early radiation survey measurements;
- Compile a complete database of measurements of long-lived fission products (^{137}Cs), actinides (U and Pu), and soil activation product radioisotopes (^{36}Cl and ^{41}Ca) using both early and recent soil samples and building surface contamination (^{36}Cl);
- Resolution of differences between recent calculations of the dose factors for exposure to beta particles and gamma rays from neutron activated soils at Hiroshima and Nagasaki;
- Parameters affecting beta and gamma doses (soil thickness, dehydration, fractionation, pedestal cloudshine, depth distribution in soil as functions of incident neutron spectra, etc.);

- Blast effects and weathering that might have moved or altered the initial location of fallout at Hiroshima and Nagasaki;
- Ground materials at Hiroshima and Nagasaki that could have been potential radiation sources due to neutron activation;
- Unrecognized sources of dose or shielding not considered in the DS02 initial radiation calculations;
- Potential dust loading during the first seconds and minutes following the blast for use in calculations of human intake and delayed radiation shielding; and
- Coupled three-dimensional hydrodynamic calculations of lofting and distribution of activated materials based on the detailed topography of the two cities, which are significantly different.

Suggestions for possible research on health effects related to potential residual radiation exposures

- While available individual data appear to be self-reported symptoms of limited accuracy and the data have been recently analyzed, further investigation of epilation or cataract dose response and threshold dose, symptoms particularly sensitive to beta radiation from residual radioactivity on skin or ground, may be needed;
- Additional investigation of beta-particle and gamma-ray skin dosimetry, taking into account the effect of age and gender on the thickness of the skin over various body parts such as the torso, head, arms and legs;
- Further study of the extrathoracic pathway for internal exposure to neutron activation products in dust particles;
- Develop separate Hiroshima and Nagasaki risk factor curves;
- Use the Hiroshima University multi-stage cancer model to determine Nagasaki spatial dose and time-dependent residual doses using Nagasaki cancer data from survivors and Nagasaki early entrants;
- Compare potential residual radiation dose to early entrants at Nagasaki to DS02 Nagasaki initial radiation doses;
- Redo putative dose estimates using appropriate uncertainty calculations and data from all surveys, correcting for weathering estimates and assuming activation of soil, seawater or worse-case materials, and estimate upper bound doses from immediate dispersion and deposition, no evacuation and no skin protection, and worse-case posture (lying on ground with full contact);
- Considering the lack of information on survivor behavior (location and activities) while in a fallout area and during evacuation from a fallout area, research survivor behaviors for a large dose cohort, which should be quantifiable and is needed for providing location or shielding factors to estimate residual radiation average and bounding doses; and
- Continue the effort to reconcile differences between the databases for atomic bomb survivors at RERF and Hiroshima University and between the DS02 and ABS93D dosimetry systems currently used by RERF and Hiroshima University.

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■■

APPENDIX A—TECHNICAL SESSION PRESENTATIONS

Overview of residual radiation exposures to neutron activation products at Hiroshima and Nagasaki (G. D. Kerr).

The time-dependent exposure rate conversion factor (ECF) for the neutron activation fallout at Hiroshima (G. D. Spriggs).

Identify dosimetry issues that resolve or bound the residual radiation dose (S. D. Egbert).

The Hiroshima and Nagasaki sample collection and analysis for the dose calculation from residual radioactivities [M. Hoshi (speaker), M. Aoyama, A. Sakaguchi, H. Kato, Y. Onda, S. Endo, T. Takatsuji, V. Stapaneno, M. Ohtaki].

Reconstruction of beta-particle and gamma-ray doses from neutron-activated soil at Hiroshima and Nagasaki (R. L. Weitz).

Evaluation of residual exposure at Hiroshima and Nagasaki: possibility of the measurements of beta-dose using retrospective luminescence dosimetry technique [V. Stepanenko (speaker), T. Kolyzshenkov, D. Dubov, A. Khailov, V. Skvortson, M. Ohtaki, M. Hoshi].

Calculation of contact beta-particle exposure of biological tissue from the residual radionuclides in Hiroshima [M. Yu. Orlov, V. F. Stepanenko, I. G. Belukha (speaker), A. M. Khailov, V. G. Skortsov, M. Ohtaki, M. Hoshi].

Parameters governing contribution of neutron-activated radionuclides to dose received by atomic-bomb survivors (K. F. Eckerman).

Effects of fallout rain on mortality and cancer incidence among the Life Span Study of Atomic-bomb Survivors [E. J. Grant (speaker), R. Sakata].

Effect of distance from hypocenter at exposure on solid cancer among Hiroshima atomic bomb survivors with very low initial radiation dose in the Dosimetry System 1986 (DS86) [M. Ohtaki (speaker), K. Otani, T. Tonda, Y. Sato, N. Hara, S. Imori, H. Kawakami, S. Tashiro, K. Aihara, M. Hoshi, K. Satoh].

Discussion and concluding remarks for technical session (I. Al-Nabulsi, M. Hoshi).

APPENDIX B—WORKSHOP PRESENTATIONS

Excess risk of solid cancer mortality among early entrants in Hiroshima City after A-bombing—using half-life of radionuclides [K. Otani (speaker), M. Ohtaki, T. Tonda, Y. Sato, N. Hara, H. Kawakami, S. Tashiro, M. Hoshi, K. Satoh].

Distance explains better than initial radiation dose for excess relative risk due to solid cancer mortality among Hiroshima atomic bomb survivors [M. Ohtaki (speaker), K. Otani, T. Tonda, Y. Sato, N. Hara, S. Imori, H. Kawakami, S. Tashiro, K. Aihara, M. Hoshi, K. Satoh].

Spatial distribution and other characteristics of reported severe epilation in the atomic bomb survivors (H. M. Cullings).

Risk regression with putative dose terms for external exposure to local radioactive fallout (H. M. Cullings).

Justification of the scenario and input data to assess the beta-to-gamma dose rate ratios in the area of wet fallout downwind from the hypocenter following the Hiroshima detonation [S. Shinkarev (speaker), V. Kryuchkov, E. Granovskaya, B. Kukhta].

Assessment of beta doses to organs and tissues located in near-surface layer due to residual radiation exposure [V. Kryuchkov (speaker), E. Granovskaya, B. Kukhta, S. Shinkarev].

Possibility of development of the reported health effects in the Japanese atomic bomb survivors due to residual radiation exposure [E. Granovskaya (speaker), V. Kryuchkov, B. Kukhta, S. Shinkarev].

Dose reconstruction in the Southern Urals, Russia—methodological aspects potentially useful for validating residual doses in Hiroshima [C. Woda (speaker), A. Ulanovski, N. Bougrov, M. Degteva, S. Romanov, O. Ivanov, P. Jacob].

Discussion and concluding remarks for workshop (G. D. Kerr, S. D. Egbert).